Preparations for the Insertion of “Long-Bo” in the Liquid Argon Purity Demonstrator

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I. ABSTRACT

When cosmic ray muons pass through liquid argon, they leave behind a trail of ionized electrons. These electrons can be then recorded by a time projection chamber to display the path of the particle through the liquid argon. Highly electronegative molecules present in the argon, such as oxygen and water, will attract the electrons and ruin the data. The purpose of the liquid argon purity demonstrator at Fermilab is to discover a new way to achieve a high level of liquid argon purity without complete evacuation of the vessel. It has been shown that the required purity can be reached in a vessel containing only a minimal amount of detector equipment by using a gaseous argon purge prior to filling the tank with liquid argon. The purpose of the liquid argon purity demonstrator now is to test whether this same level of purity can be reached with a time projection chamber in the volume. Resistance temperature detectors placed at various locations in the volume will also provide an understanding about the temperature gradients present in the tank, as well as information about convection currents. The resistances of three resistance temperature detectors were recorded at varying temperatures (-196 °C to 70 °C)—it was found that the temperature and resistance are linearly correlated. The temperature of the resistance temperature detectors is also expected to gradually rise due to the current passing through them, and we found that this expected rise in temperature should be 0.001273 °C/s. Scintillation counters hung from ladders mounted every 60° around the tank will act as the trigger to tell the time projection chamber to begin recording data, and were the other focus of the research performed. Using a coincidence module and a visual scaler, coincidences between two, three, and four scintillators were tested. We found that coincidence rates between two counters were much higher than coincidence rates between three or four counters, and attributed this discrepancy to vertical cosmic ray showers. Scintillation counters were also tested for efficiency, and it was found that four of the counters had a low efficiency and thus will not be used in the setup. The setup of the liquid argon purity demonstrator is ongoing and data is expected to be recorded in the coming months.

II. INTRODUCTION

Cosmic rays are primarily composed of protons, alpha particles, and heavier nuclei. They are believed to originate in high-energy phenomena such as quasars and supernovae across the universe. These particles, however, do not reach Earth's surface. Upon entering the atmosphere these particles will only travel a short distance before they interact with nitrogen or oxygen molecules via the strong force. This interaction produces charged pions, which themselves interact or travel about 500 m before decaying into muons. The muons do not interact via the strong force and have a longer lifetime due to time dilation, therefore making it to the ground[1].

One way to detect and measure cosmic ray muons is by use of a time projection chamber (TPC) placed in liquid argon. While passing through liquid argon, a charged particle will ionize the argon atoms and create free electrons. In the presence of an electric field, the electrons will drift through the liquid argon toward a plane of wires at the top of the TPC, where they can be detected. The liquid argon purity demonstrator (LAPD) will use a 2 m TPC (nicknamed Long-Bo) to show that electron drift over a long distance is possible.

The tank of the LAPD has a volume of 22 240 L, a diameter and height of about 3.1 m, and has the capacity to hold 28 123 kg of argon. In the past, a vessel used for this type of research would be evacuated prior to filling it with liquid argon[2]. This is important because highly electronegative impurities such as oxygen or water will attract the free electrons. Evacuation of a multi-kiloton detector is unfeasible, so the purpose of the LAPD is to show that achieving the required purity is possible by using a gaseous argon purge, to remove the atmosphere, prior to filling the tank. The LAPD will provide initial research for the long baseline neutrino experiment (LBNE), which uses liquid argon in a similar fashion to look at neutrino interactions.

III. TEMPERATURE MONITORING

It is important to understand if the argon in the tank is subject to large and fast convective currents since they may disturb the wires of the TPC. It is difficult to measure flows directly, but it is possible to measure temperatures. Temperature monitoring within the tank will be done by the use of resistance temperature detectors (RTDs). Three RTDs will be mounted on a circuit board and placed in various locations around the tank. These RTDs will measure the temperature gradient of the liquid argon in the tank to understand convection currents.

Three RTDs, soldered to a switch, were tested for linearity and stability. Figure 1 shows measurements of resistance versus temperature. Resistance measurements were obtained from a Keithley 196 DMM multimeter by placing the RTDs in an oven and adjusting the temperature. Low temperature data was obtained by placing the RTDs in liquid nitrogen. One can see from the graph that resistance and temperature share a linear relationship in this particular RTD.

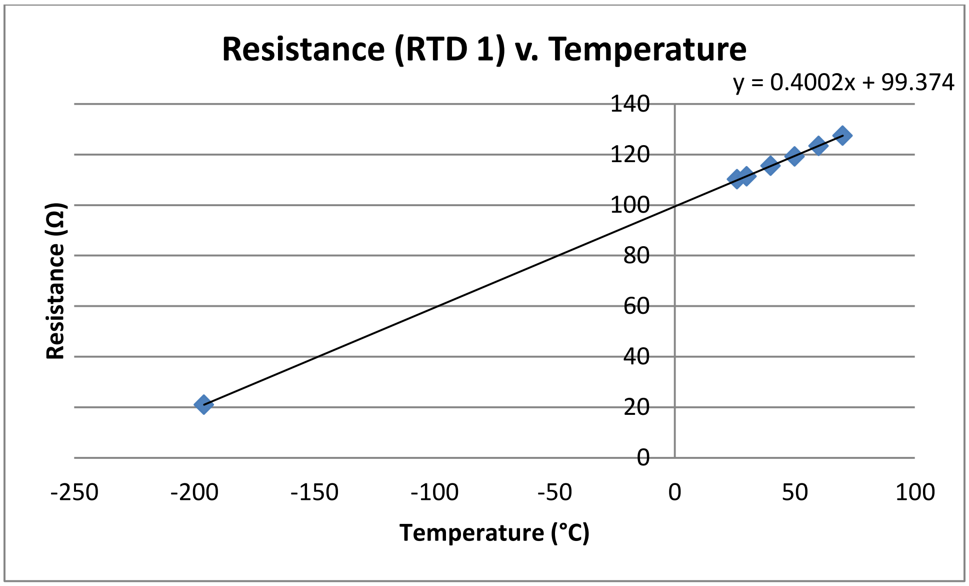

FIG. 1. The resistance of the first RTD versus the temperature in degrees Celsius.

Similar results were obtained with the other two RTDs that were tested. From this linear relationship, the temperature can be inferred from any measured resistance. Using these results we determined that the resistance of the RTD will change at a rate of 0.40 Ω/°C.

While the RTDs are in use, their temperature will gradually rise due to the electrical resistance. The expected rate of raise in temperature can be calculated using the thermal mass, power, heat input, current input, and change in temperature via the equations $P=I^2R$ and

Table 1. This table shows data for one of the RTDs for the first 3 minutes it was in use.

Time (s)	Resistance (Ohms)	Current (mA)	Power (W)	Heat (Joules)	Calculated Temp (degC)	Thermal mass (J/degC)
0	110.4823	1.7	0.000319294	0	27.73640898	0.250988033
60	110.5228	1.7	0.000319411	0.019164654	27.83740648	
120	110.5508	1.7	0.000319492	0.038339017	27.90723192	
180	110.5742	1.7	0.000319559	0.057520699	27.96558603	

$Q=C_{TH}\Delta T$ (results shown in Table 1). Using these equations and data collected, it was determined that the expected rate of raise in temperature due to electrical resistance is 0.001273 °C/s.

IV. THE TIME PROJECTION CHAMBER

The TPC is an ionization detector which has the ability to produce bubble chamber like images that show topology and ionization density. The TPC used in the LAPD is roughly 2 m in length and 30.5 cm in diameter. When a charged particle passes through the liquid argon contained within the TPC it will ionize electrons along its path. The electric field within the TPC of 50 000 V/m will cause the ionized electrons to drift uniformly toward a set of wire collection planes. The wire collection planes will then measure the drift time and position of the electrons. The ionization density that the wire planes measure can be used to identify different particles.

A. Modeling the "Long-Bo"

Long-Bo is very fragile and must be handled with care. The location of the liquid argon tank does now allow Long-Bo and its connection outside the tank to stand upright, making insertion into the tank a difficult and arduous task. A crane mounted at the top of the tank will be used to hoist the TPC up to the tank. The cable feed-through at the top of the TPC is on a hinge and can thus be bent for insertion. A model TPC was created (figure 2) to simulate the Long-Bo so insertion can be practiced.

FIG. 2. The model TPC (left) will be used to practice insertion of the real TPC (right)

The model TPC was made from two concrete tube forms, approximately 30.5 cm in diameter. The electronics at the top of Long-Bo were modeled by foam blocks wrapped with a sheet of black plastic. Clamps for the ribbon wires were created by screwing two pieces of PVC pipe, 10.2 cm in length and roughly 2 cm in diameter, to a wooden disc epoxied to the top of the tube form.

B. Sample Results

A short TPC nicknamed "Bo" was used to obtain initial results in a small tank. Figure 3 shows the raw data of a muon track through the liquid argon that was captured by Bo. Each graph represents a different plane of wires, and each line on the graphs represent a different wire. Thus, the TPC has the capability to show three different angles. The horizontal axis shows the time that each wire received the signal. Figure 4 displays the ionization density of the muon track shown in figure 3. If the particles are unknown, the ionization density can give us an idea of what particle it is. The stopping power of a particle is the average energy loss of the particle per unit length. For example, if the stopping power of a particle is large, the ionization density of the path of the particle will be high.

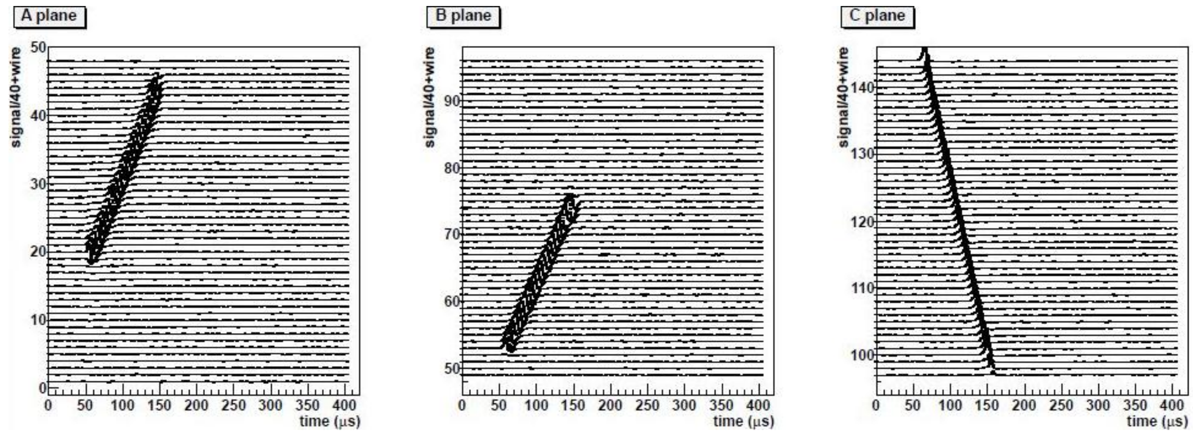

FIG. 3. A sample of a signal recorded by a time projection chamber in three different angles.

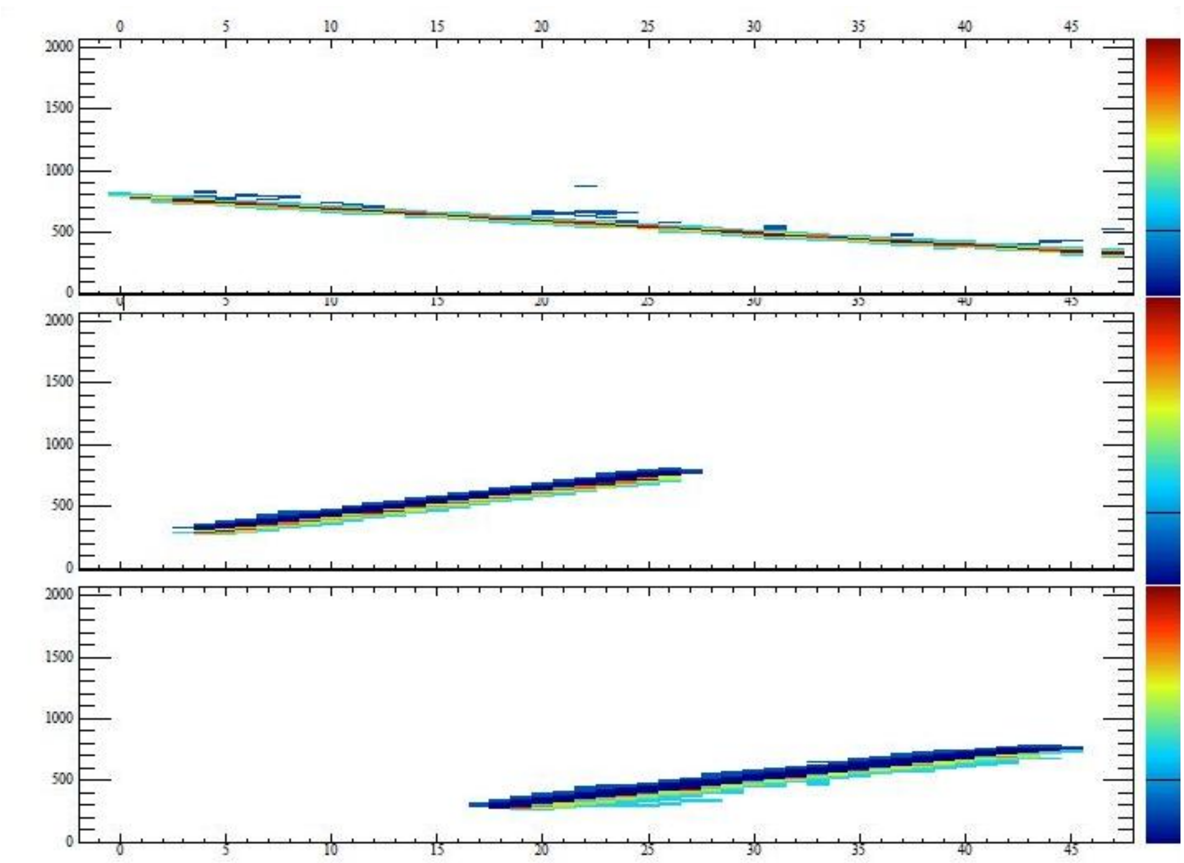

FIG. 4. The ionization density of figure 3.

The LBNE will be used to detect neutrino interactions in an effort to understand their oscillations. Figure 5 shows a sample of data that could be obtained from the LBNE. A neutrino interacts with a proton at position 1, producing a muon, proton, two neutral pions, and one positively charged pion. This can be represented by the following interation: $\nu_\mu + p \rightarrow \mu^- + p + 2\pi^0 + \pi^+$. The neutral pions decay almost instantly into four high-energy photons. The photons then move through the liquid argon a short distance and interact with an argon nucleus, producing an electron positron pair represented at positions 2, 3, 4, and 5. The lack of an ionization trail between these four positions and the neutrino interaction point is due to the fact

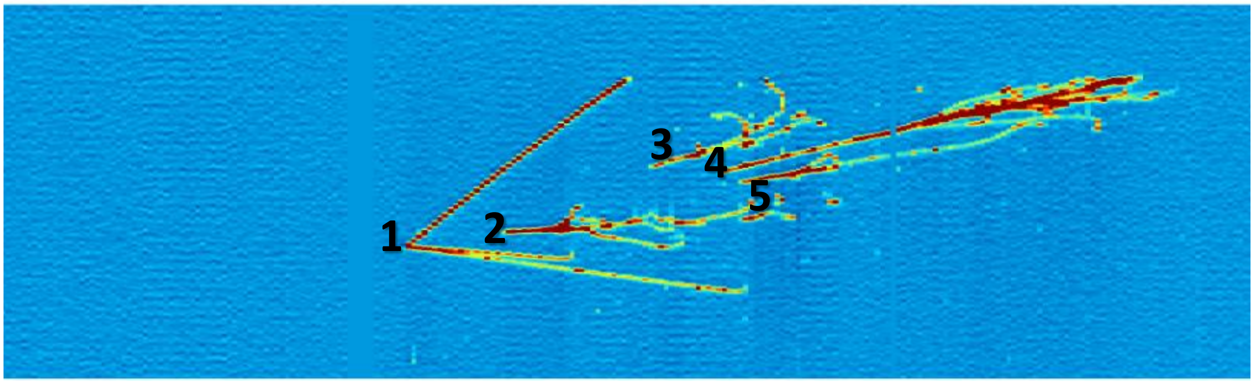

FIG. 5. A neutrino interaction in liquid argon.

that photons carry no charge and therefore will not produce a trail of electrons. The ionization density in this plot allows us to infer what particle each trail represents. For example, because the top line above position 1 is very dense, one can conclude that this is the proton because it has a high 'stopping power.'

V. SCINTILLATION COUNTERS

Scintillation counters 1.5 m in length and .15 m in width placed every 60° around the tank will provide the trigger to tell Long-Bo to begin recording data. When a cosmic ray muon passes through the scintillating material it will excite an electron from its ground state. Upon returning to its ground state, the electron will release a photon. The energy and wavelength of this photon is determined via the Stokes Shift. The Stokes Shift describes the effect that an emitted photon will have less energy (and thus a longer wavelength) than the energy it was excited with[3]. This is what allows the scintillators to work. If the emitted photon did not have less energy it would simply be re-absorbed and not travel through the plastic. The photon travels down the scintillation material via total internal reflection and upon reaching the end is guided to a photomultiplier tube (PMT).

When the photon reaches the PMT it interacts with a photocathode, ejecting electrons via the photoelectric effect. An applied voltage allows the electron to travel to the first dynode. The electron's interaction with the dynode releases more electrons, and this multiplication along subsequent dynodes causes a cascade of electrons. The cascade is collected at the anode and can then be measured as a current[4].

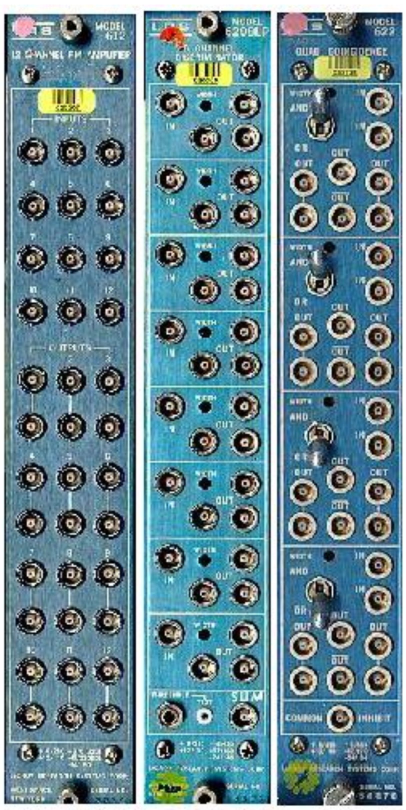

FIG. 6. Scintillator NIM setup. PMT Amplifier (left), discriminator (middle) and logic coincidence (right)

Figure 6 shows the NIM modules that all the scintillators go through. First, the signal from the PMT is amplified by a factor of ten in the LeCroy amplifier. Then, the signal goes through the LeCroy discriminator. The discriminator selects the real pulses from the noise via a minimum threshold and outputs a logic pulse of a certain time width. After the discriminator, two pulses from different scintillators are fed through the LeCroy logic coincidence. The coincidence can be set to "or," which allows two scintillators to act as one, or "and," which allows two scintillators to detect a cosmic ray muon. If the logic pulses from the discriminator coincide, the coincidence sends a signal to be recorded.

A. Counter Testing

Initially, counters were tested for light leaks and their velocity of transmission. The scintillators are wrapped in a layer of aluminum foil, followed by a layer of black plastic. The black plastic protects the scintillators from light, because if outside light reaches the PMT it will produce a false signal. Figure 7 shows what a light leak will show on an oscilloscope. The images were taken by a Tektronix oscilloscope. Position 3 shows a muon signal. Positions 1 and

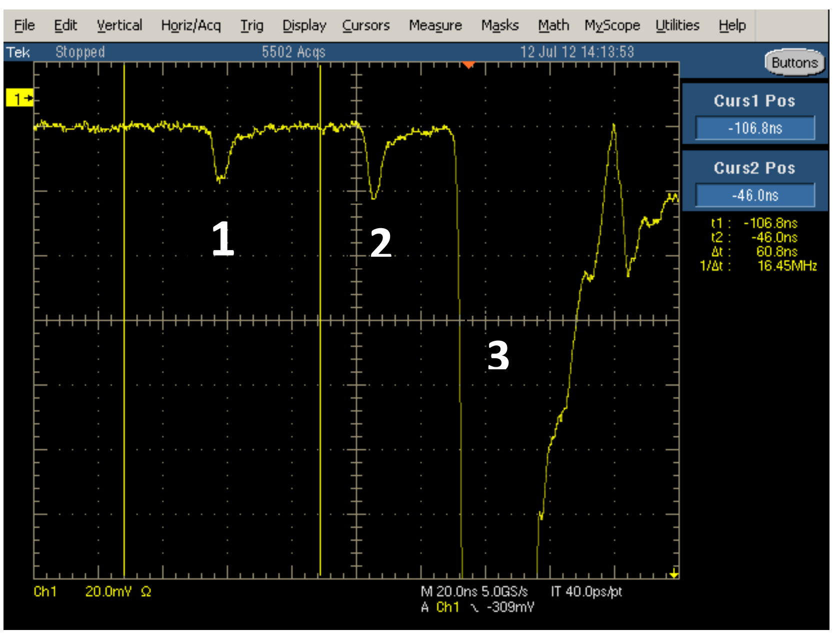

FIG. 7. Light leaks in a scintillator.

2 show what a typical light leak signal will look like. Once found, light leaks can be fixed by applying a layer of black electrical tape.

The velocity of the signal down the scintillator can also be found using the oscilloscope. A time difference can be seen while triggering on a small scintillator placed and both ends of the large one. Figure 8 shows this time difference and how it is measured on the oscilloscope. In this

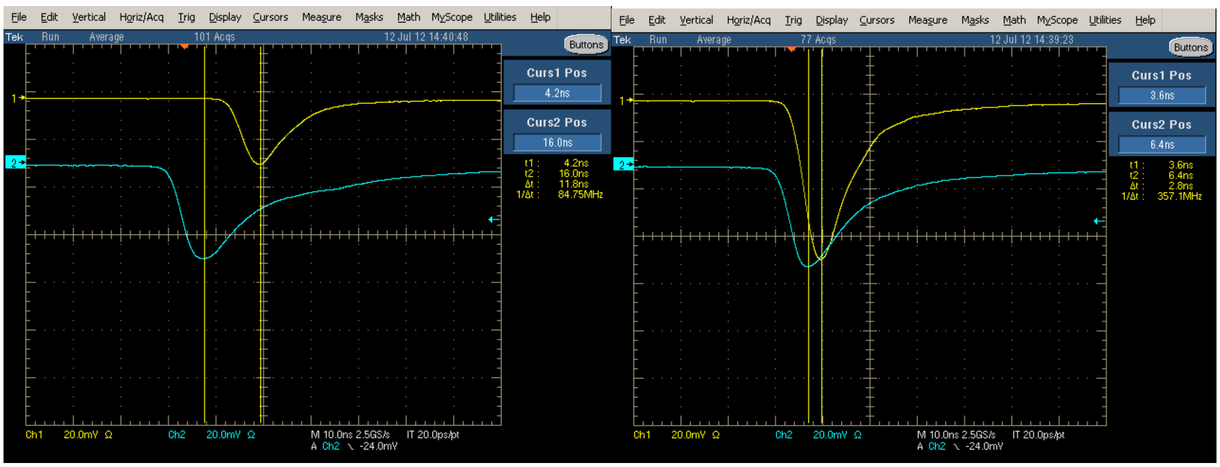

FIG. 8. Signal time difference between two ends of a scintillator.

particular instance, the time difference is 9.0 ns. The difference in length that the light had to travel is roughly 1.524 m. This tells us, that if the photon was moving in a straight path, it would only be traveling 1.693×10^{8} m/s, which is only about half the speed of light. We can also calculate the critical angle since we know the speed of light to be 2.998×10^{8} m/s. Using an inverse sine, we get a critical angle of roughly 34.4°.

B. Efficiency Testing

Counters were extensively tested for efficiency. A muon passing through two counters will generate two pulses close in time—a coincidence which can be recognized by electronics and recorded. Placing the PMT in a voltage range where it is most efficient is important because not all power supplies operate the same. If the voltage on the PMT is not in this range, a small fluctuation could mean a much lower efficiency, thus missing muons. At first to test efficiencies, four counters were placed vertically in a straight line and evenly spaced to a predetermined distance. Table 2 shows results from the initial efficiency tests. According to these results (shown in table 3), the efficiencies of counters 107 and 138 are only 73.9% and 63.5% respectively. The efficiencies were calculated by dividing the coincidence rate of all four counters by the coincidence rate of the three counters without the counter whose efficiency is being measured.

Table 2. Efficiency calculation for counters 107 and 138

Distance	Number of Counters	Actual Rate (Hz)	Rate Error	Efficiency	Counter Removed	Efficiency Error
2	4	0.0383333	0.00565	---------	---------	---------
2	3	0.0533333	0.00667	0.719	107	0.0562
2	3	0.0575	0.00682	0.667	138	0.0568
2	2	0.0933333	0.00882	---------	---------	---------
3	4	0.0183333	0.00553	---------	---------	---------
3	3	0.0233333	0.00624	0.786	107	0.154
3	3	0.0316667	0.00726	0.579	138	0.215
3	2	0.0583333	0.00986	---------	---------	---------

Table 3. Final efficiency results of table 2.

Counter	Efficiencey	Uncertainty	Threshold (mV)	Voltage (V)
107	0.73669427	0.052776271	10	1720
138	0.6483622	0.054874618	10	1400

One potential discrepancy we discovered was that the coincidence rate between the outer counters was much higher than the coincidence rate with three or four counters. To understand this inconsistency, two counters were placed flat on the ground various distances apart. A straight cosmic ray would not be able to create a coincidence between two flat counters. Table 4 shows the results from this test. The rate that two counters will randomly have a coincidence was

Table 4. Data with counters placed flat on the ground.

Time (s)	Separation (m)	Counts #2	Counts #138	Counts/s #2	Counts/s #138	Random Probability	Predicted Randoms	Coincidences	Coincidences/s	Error
1800	6.096	135240	123151	75.1333	68.4172	0.000514	0.925275	140	0.077777778	0.00657
1800	7.62	121686	125376	67.6033	69.6533	0.0004709	0.847584	126	0.07	0.00624
1800	9.144	129068	119564	71.7044	66.4244	0.0004763	0.857327	114	0.063333333	0.00593
1800	10.668	122705	106401	68.1694	59.1117	0.000403	0.72533	90	0.05	0.00527
1800	12.192	138037	125577	76.6872	69.765	0.000535	0.963015	87	0.048333333	0.00518
1800	13.716	108519	124233	60.2883	69.0183	0.0004161	0.74898	81	0.045	0.005

determined by multiplying the two individual counter rates together by the sum of the widths. As seen in table 4, the predicted number of random coincidences is always around 1 in 30 minutes. Therefore, the coincidences seen between the two flat counters must have come from a different source. One idea is that these "fake" coincidences come from extensive air showers (EAS). When a cosmic ray enters the atmosphere it creates a cascade of particles that, when they reach the ground, could have a radius of a few kilometers. If the particles from these air showers reach the ground at the same time, they could potentially create a coincidence between two counters. Although there is no way of preventing this, it shows why the coincidence between two counters was so much higher, and may explain why the measured efficiencies of the tested counters were so low.

Since testing efficiencies with the counters vertically produced bad results, it was decided efficiencies should be tested for each counter by placing three scintillators on top of one another horizontally. It was also decided that the efficiency would be tested at different voltages applied to the PMT. Figure 9 shows the results of testing counter 138. As the applied voltage nears

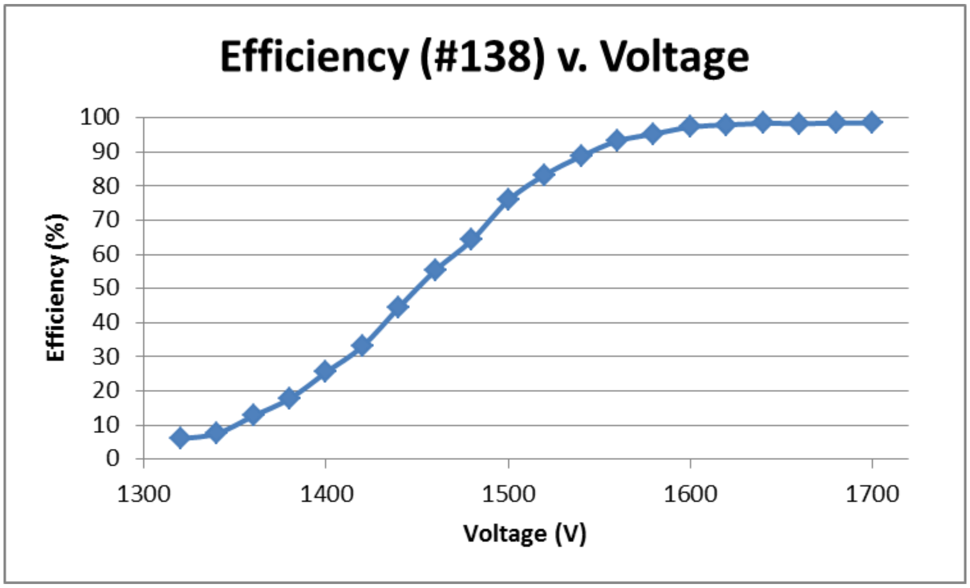

FIG. 9. Plateu curve of the efficiency of counter 138 versus applied voltage.

1700 V, the efficiency of the counter levels off around 98%. Similar curves were obtained for each counter, so a range of operating voltages was determined, as well as the true efficiency of each counter.

C. Setup and Results

Three counters placed vertically every 60° around the tank, shown in figure 10, provide the trigger for the TPC to begin recording data. The top two counters act as one large counter by

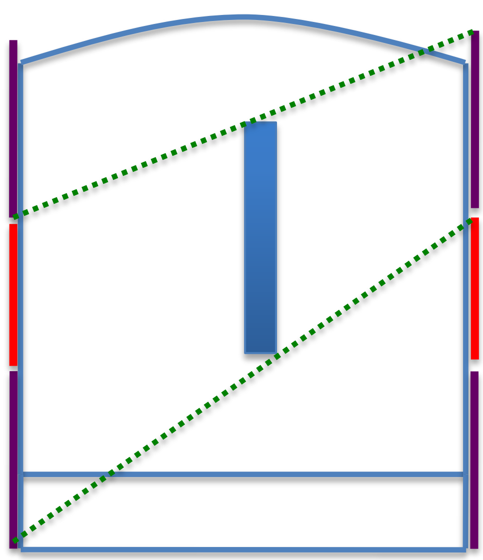

FIG. 10. (not to scale) Counter positions from side view.

wiring them together as an “or” in the logic unit. These two counters are then wired together with the lower counter on the other side of the tank via the logic unit to obtain the largest number of angles possible through the TPC. A coincidence between the two sides will then tell the TPC to record data.

To mount the scintillators on the sides of the tank, aluminum holders were made to hang them on ladders. Figure 11 shows the holders. The holders were designed to hang closely to the

FIG. 11. Aluminum holders to hang the scintillators on the ladders.

ladder and so that three scintillators could be placed on each ladder at once. Figure 12 shows three scintillators mounted on one of the ladders.

FIG. 12. Three scintillators mounted on a ladder outside of the LAPD tank.

Once all eighteen scintillators were placed on the ladders, coincidences were looked at using the oscilloscope. Figure 13 shows the oscilloscope read-out for a coincidence. Channel 1 and 2 (yellow and blue) are the top two scintillators. Channel 3(pink) is the bottom scintillator on the other side of the tank. Channel 4 (green) is the logic pulse from the coincidence that shows a cosmic ray muon passed through both scintillators within the 50 ns time window. The horizontal divisions on the oscilloscope readout are 10 ns each, so one can see that the muon passed through the first scintillator, and roughly 10 ns later passed through the second. This is consistant with the muon traveling near the speed of light. The two ladders were roughly 3.66 m apart, so taking the muon's velocity to be the speed of light, it should have reached the other scintillator in roughly 12.2 ns. This show us that the setup is currently working as it should and insertion of

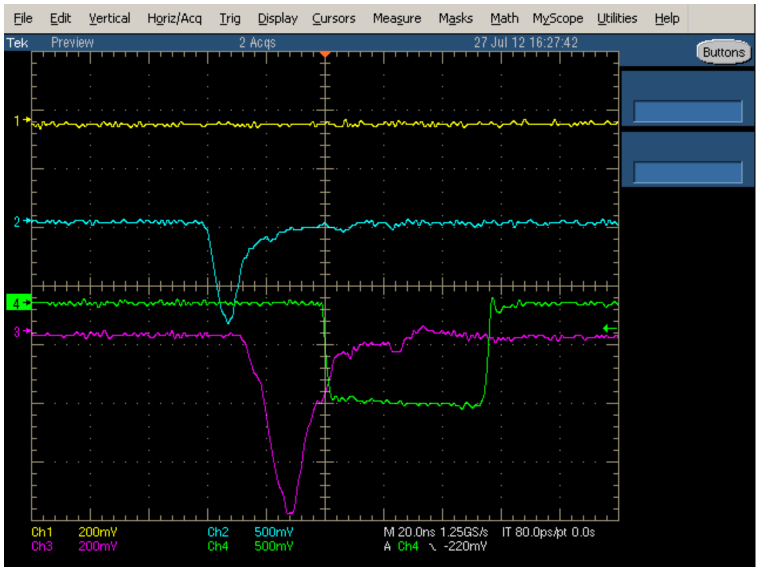

FIG. 13. Cross-tank coincidence.

Long-Bo should occur within the coming months.

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